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December 29, 2006

REF: ARPA Order No. S597/00/03
Program Code: 3Z30/4920

COR
NSWC/Dahlgren Division
Attn: Craig LaMoy
17320 Dahlgren Road, Code B57
Dahlgren, VA 22448

Dear Mr. LaMoy:

Enclosed please find New World Associates' Final Technical Report for the Toxic Industrial Contaminant (TIC) Filter Development Program for the ARPA order referenced above.

Please call Jennifer Conway or me at (540) 373-1435 if you have questions about our technical report or invoice.

Sincerely,

Jason J. Malik

Jason Malik
Contracts Manager

Encl: as stated above

cc:
Wayne Bryden/DARPA
Jan Prichard/DARPA
N. Tina Stuard/DARPA
DARPA/Library
DTIC (via electronic mail)

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14. ABSTRACT
New World Associates in association with ECBC, Hunter Manufacturing, and Portsmouth Aviation has proved the concept of a layered bed CBR/TIC filter. Filters have been developed that provide toxic industrial chemical protection in addition to the chemical, biological and radiological protection provided by the standard M98 filter set. This concept can be extended to other TICs in addition to the ones selected for this effort. A layered filter can be made with a sorbent selected for the specific TIC(s) of concern for a particular application. It has been shown that it is possible to retrofit these filters into existing collective protection (ColPro) systems with housings designed to hold the M98 filter. With relatively minor modifications to accommodate the increase in pressure drop and a replacement housing cover, these filters can be installed in any land based ColPro system. These filters are complete such that with minor modifications they could be ready for production very quickly if there was a demand for them. The majority of filters passed the particulate and chemical tests and proved they would remove the contaminants as designed.

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Technical Report NW002566

CBR/TIC Filter Design and Evaluation

December 2006

Thomas Van Doren Ph.D.
Ezra Johnson
William Whittier

Sponsored by

Defense Advanced Research Projects Agency
Special Projects Office (SPO)
Program: Defense Against Chemical, Biological, and Radiological Weapons

Technical POC

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17320 Dahlgren Road, Code B57
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FOREWARD

New World Associates, Inc. is pleased to submit this report entitled, "CBR/TIC Filter Design and Evaluation." This report, authored by Dr. Thomas Van Doren, Ph.D., Mr. William Whittier, and Mr. Ezra Johnson, presents work performed for the Defense Advanced Research Projects Agency (DARPA) under the direction of Mr. Craig LaMoy (COR). Funding was provided under Contract No. HR0011-04-C-0100, DARPA Order No.S597/00/03.

This report describes the research and development work performed by New World for the development and evaluation of a chemical, biological, and radiological (CBR) and toxic industrial chemical (TIC) filter concept for collective protection (ColPro) system applications. The purpose of this work is to develop a filter that will add TIC capabilities to the standard capabilities of the M98 filter system using existing filter housings. This report presents the findings of this development and evaluation, as well as recommendations concerning future TIC development.

EXECUTIVE SUMMARY

New World Associates, Inc. in association with Edgewood Chemical and Biological Center (ECBC), Hunter Manufacturing Company, and Portsmouth Aviation has proved the concept of a layered bed chemical, biological, and radiological (CBR)/toxic industrial chemical (TIC) filter. Filters have been developed that provide TIC protection in addition to the CBR protection provided by the standard M98 filter set. This concept can also be extended to other TICs in addition to the ones selected for this effort.

A layered filter can be made with a sorbent selected for the specific TIC(s) of concern for a particular application. It has been shown that it is possible to retrofit these filters into existing collective protection (ColPro) systems with housings designed to hold the M98 filter. With only relatively minor modifications to accommodate the increase in pressure drop and a replacement housing cover, these filters can be installed in any land-based ColPro system. These filters are complete such that with minor modifications they could be ready for production very quickly if a demand arose. The majority of filters passed the particulate and chemical tests and proved they would remove the contaminants as designed.

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INTRODUCTION

The M98 filter set is the primary filter set used to protect military and government buildings, ships, and shelters from airborne attacks. The M98 filter set was created to filter chemical, biological, and radiological (CBR) agents from the air (Figure 1). The filter set consists of a particulate HEPA filter and a gas or chemical filter. The HEPA filter was designed to remove particulates such as biological and radiological warfare agents (BRWA). The chemical filter was designed to provide gas filtration for chemical warfare agents (CWAs). Due to recent events, the likelihood of a chemical attack by a terrorist organization using toxic industrial chemicals (TICs) has become a much greater concern. There are many TICs in use in standard industrial processes and thus they are relatively easy to obtain. Unfortunately, the M98 gas filter was not designed to filter these TICs and consequently many chemicals are not removed by this filter.

Figure 1. M98 Filter Set

The radial flow CBR/TIC filter developed by New World Associates, Inc. (New World) is designed to maintain the capabilities to remove CWAs and BRWAs similar to the M98 filter set. In addition, the CBR/TIC filter will provide gas filtration for a selection of TICs. Thus, the CBR/TIC filter will address a major vulnerability of the M98 filter set.

The objective of the CBR/TIC filter project is to design a filter that will add TIC filtration capabilities, as well as retrofit into existing M98 filter housings. Thus, airflow capacity for the radial flow CBR/TIC filter is set at 200 cfm. Outer diameter and length dimensions are identical to the M98 CBR filter. A M98 filter housing is shown in Figure 2.

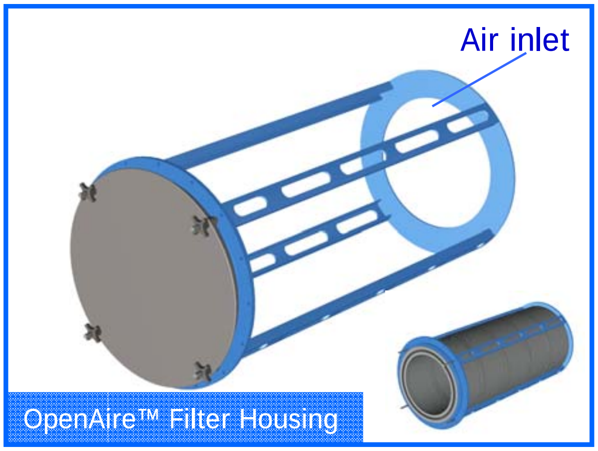


Figure 2. Housing for Radial Flow CBR/TIC Filter

TIC SCENARIO

New World's first task in the development of the CBR/TIC filter was to generate a threat scenario for which the filter should be designed. The threat scenario included chemicals the filter should remove, as well as expected concentrations and total amount of chemicals expected to be encountered. To begin, New World started with a list of TICs from the International Task Force 25 titled Hazards from Toxic Industrial Chemicals from April 1998 (ITF-25). This list divides the TICs into high, medium, and low threat categories. The high threat chemicals from the ITF-25 list are shown in Figure 3. The list was chosen as a starting point and then reduced to those chemicals for which the standard M98 filter was known to be ineffective. The list was further reduced to only chemicals identified as threats by other sources. Additionally, the list was limited to chemicals for which good threat information (concentrations and total amount of chemical) was available. Figure 4 details the reduced list of five (5) chemicals.

ITF-25 High Threat List

- Ammonia
- Arsine
- Boron trichloride
- Boron trifluoride
- Carbon disulfide
- Chlorine
- Diborane
- Ethylene oxide
- Fluorine
- Formaldehyde
- Hydrogen bromide
- Hydrogen chloride
- Hydrogen cyanide
- Hydrogen fluoride
- Hydrogen sulfide
- Nitric acid, fuming
- Phosgene
- Phosphorus trichloride
- Sulfur dioxide
- Sulfuric acid
- Tungsten hexafluoride

Subset of ITF-25:

- *Chemicals for which ASZM-TEDA used in M98 is ineffective*
- *These chemicals also identified by other sources as threats*

Reduced List

- Ammonia (NH_3)[1,2,3,4,5]
- Carbon disulfide (CS_2) [1,2,3,4,5]
- Ethylene oxide (EO) [1,2,3,4,5]
- Formaldehyde (H_2CO)[4]
- Nitric acid, fuming[1,2,4,5] ($HNO_3 \rightarrow NO_2$)

Sources:

1. ECBC – Karwacki
2. NSWCDD – LaMoy
3. NATO
4. USACHPPM TIC Info Card
5. DOT

Figure 3. TIC Threat Scenario Chemical List Reduction

From the reduced list of five (5) chemicals, two (2) TICs for this project were chosen, as shown in Figure 4. Since three (3) chemicals are not readily available in potent form or they are too difficult to

remove with the current constraints and available filter sorbents, they were removed from the list. Thus, ammonia and ethylene oxide were identified as TICs of concern for this project.

Note that this final list does not signify that these are the only TICs for which there should be concern or that these chemicals are the most dangerous. Rather, ammonia and ethylene oxide were chosen because they represent real threats from which protection is possible and for which credible threat concentrations were available.

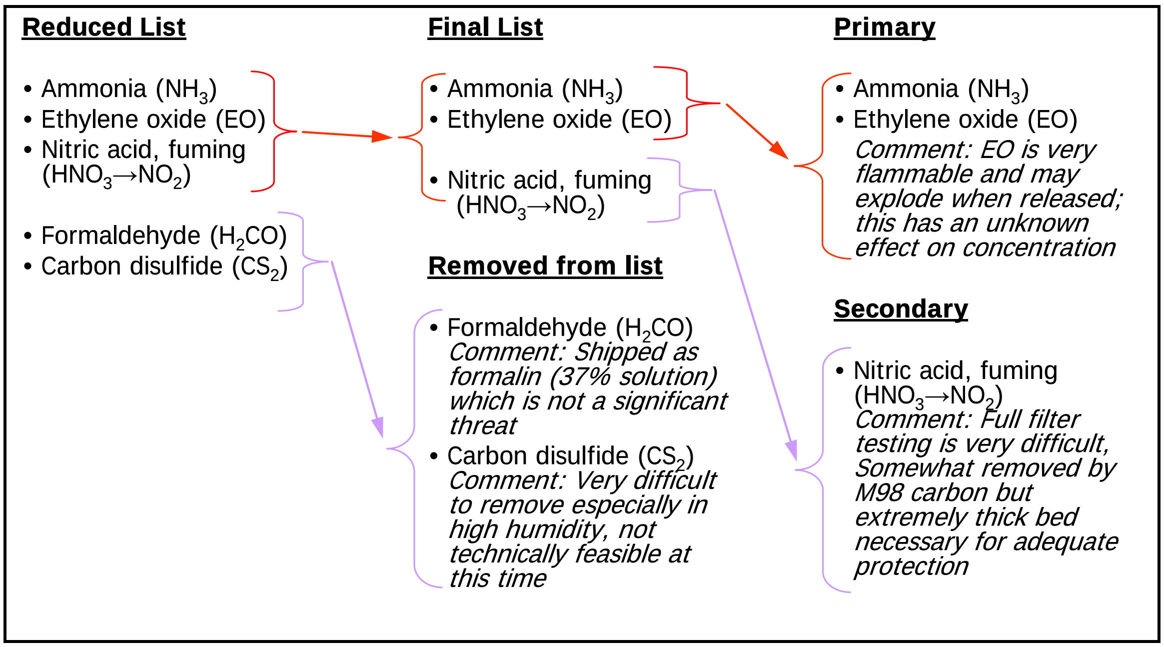


Figure 4. TIC Threat Scenario Final List Selection

In addition to selecting the TICs of concern, New World was also required to select a target filter life for the TICs and CWA simulants. Table 1 lists the proposed filter life targets for the TIC filter compared to the requirements and actual filter life for the M98 filter. The filter life is measured in a concentration (mg/m^3) over an elapsed time (min) or Ct (mg-min/m^3). The Ct's for the CWA simulants (DMMP and CK) were chosen with a reduction from the M98 filter requirements to allow for more flexibility in designing the CBR/TIC filter while still providing adequate protection from a CWA attack. Below is an excerpt from the M98 performance specification (MIL-PRF-51527B) on the useful life of the M98 filter. It should be noted (as it is in the excerpt below) that the M98 filter set was designed for battlefield use to protect against multiple attacks of relatively high gas concentrations. Thus, for many applications it may be considered to be overdesigned, in that multiple attack scenarios are unrealistic.

Useful life. A useful life goal for the gas filter is 2 years or more of peace time use with no more than 10% degradation in gas life. The useful life is the maximum period of time an unpackaged item can remain fit for use. Exposure to moisture is known to diminish gas life. A DMMP gas life of 60 minutes and challenge of 5000 mg/m3 is equivalent to 15 chemical attacks, whose average concentration---time is 20,000 mg-min/m3. Useful life goal for the particulate filter is 4 years or more of peace time use.

The Ct's for the TICs were based on concentrations and times from threat scenarios were made available by Mr. Craig LaMoy at Naval Surface Warfare Center, Dahlgren Division (NSWCDD). These Ct numbers may not be ideal, however, they are meant to be a reasonable compromise with the tradeoff between TIC and CWA filter life inherent in the two (2) bed design of this filter.

Chemical	**TIC Filter Proposed CT ($mg\text{-}min/m^3$)**	**M98 Filter Requirements ($mg\text{-}min/m^3$)**	**Hunter M98 Filter Actual CT ($mg\text{-}min/m^3$)**
DDMP	200,000	300,000	360,000
CK*	40,000 @ 2 Years	48,000 @ 2 Years	160,000 (48K @ 2 Years)
Ammonia†^	50,000	0	8,000
Ethylene Oxide†^	50,000	0	300

* Requirements for CK are from filter design information provided by ECBC and are not actual requirements per the filter performance specification. All CK performances requirements are for media samples (tube tests) that do not test the actual filter

† NSWCDD and ECBC recommendations

^ Challenge concentration of 1,000 mg/m^3

Table 1. Filter Life Requirements

PRELIMINARY DESIGN

Concept

The basic concept of the radial flow CBR/TIC filter consists of annular layers of filter media for particulate/aerosol and gaseous agents (Figure 5). The geometry of the filter builds on the robust and proven architecture of M98 and NATO filter sets (Figure 6). The airflow path is in through the center, then out radially though the filter layers.

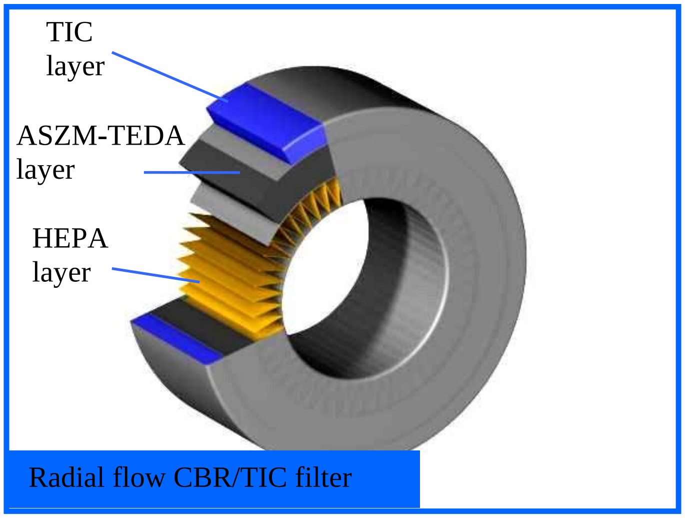


Figure 5. Radial Flow CBR/TIC Filter

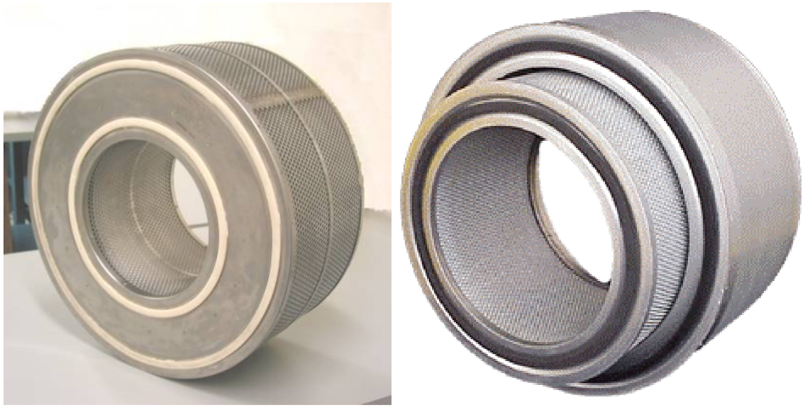


Figure 6. NATO (left) and M98 (right) CBR Filters

In order to add a TIC layer to the existing M98 filter there were three (3) variables that could be changed:

- Diameter of internal airflow space
- Thickness of the HEPA filter layer
- Thickness of the carbon filter layer

The design efforts of this project entailed finding an optimal balance between these three (3) variables and the thickness of the TIC layer itself.

In order to identify the best overall design, the CBR/TIC filter project was arranged to create multiple filter designs based on the general concept outlined above. Edgewood Chemical and Biological Center (ECBC), New World, and Hunter Manufacturing Company (Hunter) created designs for this project. ECBC created the first gas bed design with New World designing the mechanical packaging and HEPA filter. Hunter designed another version of the gas filter using the same HEPA filter as New World designed for the ECBC filter set.

Portsmouth Aviation Ltd. (Portsmouth Aviation) also designed a version of the complete CBR/TIC filter including the HEPA and gas filter. Portsmouth Aviation decided to independently fund their design and development work to allow for the retention of intellectual property rights on their filter design. Portsmouth Aviation remained part of the project and submitted their design to be tested with the other filters.

Concept Feasibility

With the additional adsorbent layer (and therefore the additional thickness) added to the CBR/TIC filter compared to the standard M98 filter, an increase in pressure drop across the filter was expected. The actual results from the pressure drop testing can be seen in the Filter Testing section of this report. A feasibility study was conducted to determine what system changes the additional pressure drop would require and if the retrofit of CRB/TIC filters into the M98 systems is feasible. The estimates for pressure drop through components of a typical filter system for both the M98 and CBR/TIC filters are shown in Table 2. As shown, the CBR/TIC filters were expected to add a little over 3 inches of pressure drop to the filter system.

	TIC Filter System		M98 Filter System	
	Building	Ship	Building	Ship
Pressure Drop Sources	**dP (i.w.g)**	**dP (i.w.g)**	**dP (i.w.g)**	**dP (i.w.g)**
HEPA/Prefilter (Dirty)	3.8	3.3	3.5	3.0
Chemical Filter System	7.0	7.0	4.0	4.0
Mechanical System Losses	4.5	4.5	4.5	4.5
Zone Pressure	0.3	2.0	0.3	2.0
Total	15.6	16.8	12.3	13.5
Fan Capable of Pressure?	COTS Centrifugal	Need New Fan	COTS Centrifugal	Mil-Spec Vaneaxial

Table 2. TIC vs. M98 Filter System Pressure Drops

The first task was to verify that the total pressures could be handled by standard available fans. Therefore, fans for a wide range of flow rates were considered. Building ColPro systems typically use commercial off-the-shelf (COTS) centrifugal fans. The range of centrifugal fans available at different flow rates with the power required for different pressure drops are shown in

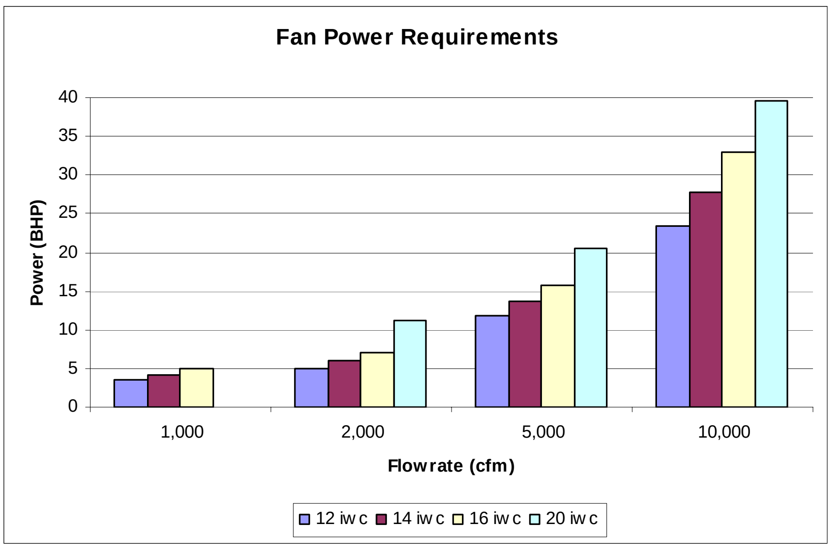


Figure 7. As shown, COTS fans are available with the increased pressure drop required up to 20 i.w.g. The increase in power requirements is commensurate with the increase in pressure drop so the additional power required should not be a significant burden. Ship ColPro systems require a vaneaxial fan that has passed both shock and vibration tests and is approved by the U.S. Navy. Currently, the available fans can only handle a maximum 14 i.w.g. pressure drop. Thus, a new fan would have to be approved by the U.S. Navy to enable CBR/TIC filters to be retrofitted into ship ColPro systems.

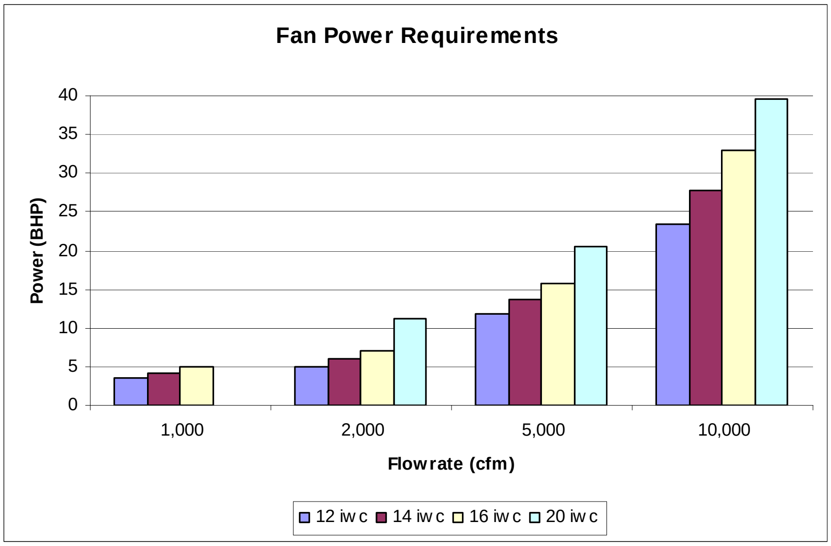


Figure 7. Standard Centrifugal Fans for CPS

In order to retrofit the CBR/TIC filter into existing ColPro systems to replace M98 filters, a new housing cover was necessary due to the change in diameters discussed above. A new cover was designed to fit the TIC filter (Figure 8).

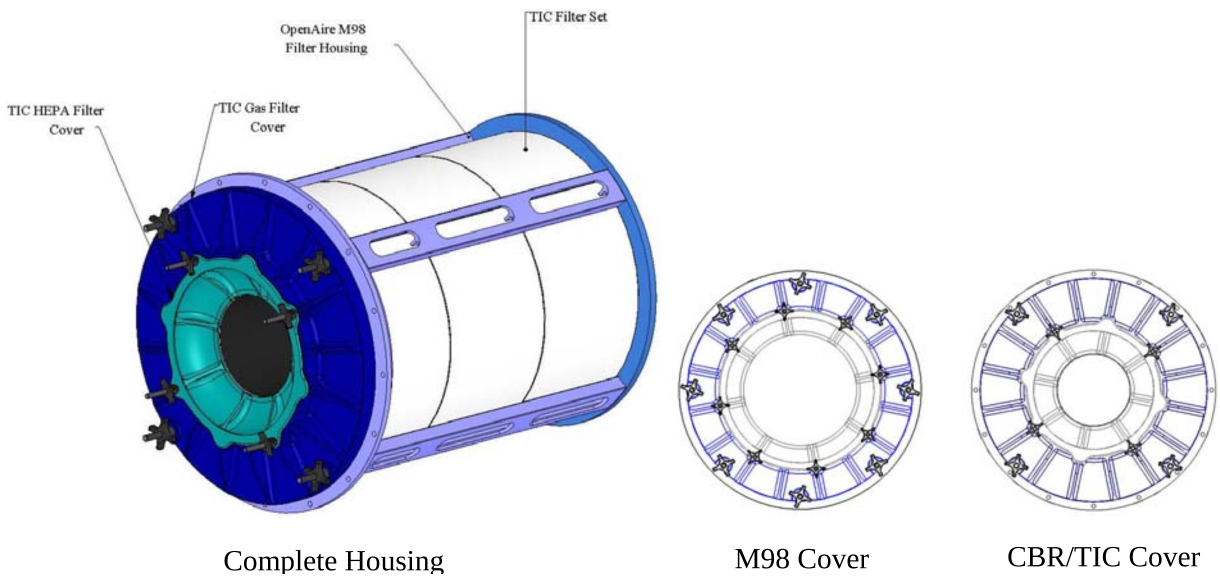
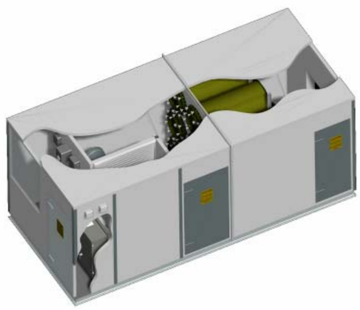


Figure 8. CBR/TIC Housing Cover

The feasibility of retrofitting the CBR/TIC filters into a building M98 filter system was verified by considering three (3) specific cases to determine what modifications would be necessary to support the retrofit. Case 1 consists of three (3) AirePod™ ColPro systems (one (1) 9,000 cfm and two (2) 8,000 cfm) installed at a specific military base (Figure 9). The AirePods contain either eight (8) or nine

(9) 5-deep Navy style M98 filter tubes (eight (8) used for 8,000 cfm, nine (9) used for 9,000 cfm). All three (3) systems use identical fans run at matching rpm for desired airflow. These AirePods were designed for 12 i.w.g. pressure head to the fans. The CBR/TIC filters will fit in the existing housings for these systems. A modified filter housing cover would need to be supplied for each tube. Good flow balance will be maintained with the change in filters. As discussed above, the CBR/TIC filters will add an additional 3-4 i.w.g. of pressure to the systems. This additional pressure capability is easily obtained using the same fan with the addition of a higher HP motor producing faster fan rotation. The required change can be seen in the fan performance chart shown in Figure 9.



BAF SWSI 200 & ACV 200

Outlet Area - 2.30 ft^2 Wheel Dia. - 20.00 Inches Tip Speed - 5.24 x RPM Max. BHP = 0.68 (RPM÷1000)^3

CFM	OV	10" SP		11" SP		12" SP		13" SP		14" SP		15" SP		16" SP		17" SP		18" SP		19" SP		20" SP	
		RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP
5520	2400	2696	11.66																				
5980	2600	2727	12.51	2838	13.82	2950	15.18																
6440	2800	2772	13.49	2875	14.80	2978	16.18	3082	17.62	3186	19.09												
6900	3000	2825	14.58	2923	15.93	3020	17.32	3116	18.75	3213	20.25	3309	21.78	3407	23.38								
7360	3200	2882	15.73	2978	17.16	3071	18.59	3162	20.04	3253	21.55	3343	23.09	3433	24.68	3524	26.33	3615	28.01	3706	29.73		
7820	3400	2943	16.94	3036	18.43	[illegible]	[illegible]	3215	21.46	3302	23.00	3388	24.56	[illegible]	[illegible]	3558	27.81	3642	29.49	3728	31.25	3814	33.03
8280	3600	3007	18.21	3097	19.77	3185	21.34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3521	27.80	3602	29.47	3682	31.16	3762	32.89	3842	34.68
8740	3800	3075	19.57	3162	21.18	[illegible]	[illegible]	3331	24.47	3414	26.16	3495	27.85	[illegible]	[illegible]	3653	31.27	3730	33.00	3806	34.74	3882	36.53
9200	4000	3145	21.01	3230	22.69	3313	24.39	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3632	31.39	3708	33.17	3783	34.95	3857	36.76	3930	38.58
9660	4200	3217	22.52	3300	24.27	[illegible]	[illegible]	3460	27.80	3538	29.61	3615	31.43	[illegible]	[illegible]	3766	35.14	3840	37.02	3912	38.88	3983	40.75
10580	4600	3368	25.85	3447	27.72	3524	29.60	3600	31.52	3674	33.43	3747	35.38	3819	37.34	3890	39.32	3960	41.31				
11500	5000	3527	29.58	3601	31.56	3675	33.58	3747	35.61	3818	37.65	3888	39.72	3957	41.81								

MAXIMUM RPM: Class I — 2093 Class II — 2648 Class III — 3377 Class IV — 3730

Figure 9. Case 1 ColPro System Retrofit

Case 2 is a 4,000 cfm ColPro system installed at a government facility (Figure 10). It consists of four (4) 5-deep Navy style M98 filter tubes. This system has approximately 8-10 i.w.g. of pressure drop. The retrofit for this system is similar to the previous case. The required additional pressure can also be obtained using the same fan with a higher HP motor producing faster fan rotation (Figure 10).

HDBI-150 — BELT DRIVE RATING TABLES
Ratings at 70°F., .075 Density, Sea Level

WHEEL Dia. - 15.00"
OUTLET O.D. Size - 11.38" x 16.75" Area - 1.28 Sq. Ft. I.D.
INLET O.D. Size - 16.13" Area - 1.39 Sq.Ft. I.D.
SEE PAGE 24 FOR MAX. WHEEL RPM & WR².

All wheels are HDBI type
Class II = light face above Class III
Class III = bold face
Class IV = italic face below Class III

VOLUME CFM	O.V. FPM	11" SP RPM	11" SP BHP	12" SP RPM	12" SP BHP	13" SP RPM	13" SP BHP	14" SP RPM	14" SP BHP	15" SP RPM	15" SP BHP	16" SP RPM	16" SP BHP	17" SP RPM	17" SP BHP	18" SP RPM	18" SP BHP
3000	2343	3621	8.25	3763	9.17	3899	10.11	4031	11.07								
3250	2539	3656	8.66	3798	9.61	3934	10.58	4066	11.57	4192	12.58	4315	13.62	4434	14.68		
3500	2734	3705	9.15	3833	10.06	3970	11.06	4101	12.08	4227	13.13	4350	14.19	4469	15.28	4584	16.39
3750	2929	3774	9.75	3896	10.67	4013	11.60	4136	12.61	4263	13.69	4385	14.78	4504	15.90	4619	17.04
4000	3125	3843	10.39	3965	11.34	4081	12.30	4194	13.29	4303	14.29	4420	15.39	4539	16.53	4654	17.70
4250	3320	3914	11.05	4035	12.04	4151	13.04	4263	14.06	4371	15.10	4476	16.15	4579	17.21	4690	18.38
4500	3515	3991	11.80	4105	12.78	4221	13.82	4332	14.87	4440	15.94	4545	17.02	4647	18.12		
4750	3710	4071	12.59	4184	13.61	4294	14.64	4403	15.72	4510	16.82	4615	17.94				
5000	3906	4151	13.43	4264	14.48	4373	15.55	4478	16.64	4581	17.74	4685	18.89				
5250	4101	4233	14.31	4345	15.40	4453	16.51	4558	17.63	4659	18.76						
5500	4296	4326	15.25	4427	16.37	4534	17.51	4638	18.67								
5750	4492	4426	16.27	4521	17.40	4616	18.56										
6000	4684	4528	17.33	4621	18.51	4712	19.70										

Power rating (BHP) does not include drive losses. Performance shown is for installation type B-Free inlet, Ducted outlet. Performance ratings do not include the effects of appurtenances in the airstream.

Figure 10. Case 2 ColPro System Retrofit

Case 3 is a 12,000 cfm ColPro system also installed at a government facility (Figure 11). It has 12 5-deep Navy style M98 filter tubes. This system has approximately 11.5 i.w.g. pressure drop. The required additional pressure can be obtained with the same fan housing. The fan wheel would be replaced with a higher class wheel and the motor would be replaced with a higher HP motor producing faster fan rotation (Figure 11).

HDBI-220 — BELT DRIVE RATING TABLES
Ratings at 70°F., .075 Density, Sea Level

WHEEL Dia. - 22.25"
OUTLET O.D. Size - 16.88" x 24.88" Area - 2.84 Sq. Ft. I.D.
INLET O.D. Size - 24.63" Area - 3.24 Sq.Ft. I.D.
SEE PAGE 24 FOR MAX. WHEEL RPM & WR².

All wheels are HDBI type
Class II = light face above Class III
Class III = bold face
Class IV = italic face below Class III

VOLUME CFM	O.V. FPM	13" SP RPM	13" SP BHP	14" SP RPM	14" SP BHP	15" SP RPM	15" SP BHP	16" SP RPM	16" SP BHP	17" SP RPM	17" SP BHP	18" SP RPM	18" SP BHP	19" SP RPM	19" SP BHP	20" SP RPM	20" SP BHP
6400	2253	2620	20.90	2718	22.93	2812	25.01										
7000	2464	2624	21.88	2721	23.99	2815	26.14	2906	28.33	2994	30.57	3080	32.85				
7600	2676	2627	22.88	2725	25.05	2819	27.28	2910	29.55	2998	31.86	3084	34.21	3167	36.60	3248	39.03
8200	2887	2631	23.87	2728	26.13	2822	28.42	2913	30.76	3001	33.15	3087	35.57	3170	38.04	3251	40.54
8800	3098	2660	25.15	2741	27.31	2826	29.57	2917	31.99	3005	34.45	3091	36.94	3174	39.48	3255	42.06
9400	3309	2694	26.53	2775	28.76	2854	31.03	2930	33.34	3008	35.75	3094	38.32	3177	40.93	3258	43.59
10000	3521	2729	27.97	2810	30.28	2888	32.62	2964	35.00	3038	37.42	3109	39.88	3181	42.39	3262	45.12
10600	3732	2780	29.74	2845	31.85	2923	34.27	2999	36.72	3072	39.22	3144	41.75	3213	44.31	3281	46.90
11200	3943	2843	31.83	2906	33.98	2967	36.14	3034	38.51	3107	41.08	3178	43.68	3248	46.32	3315	48.99
11800	4154	2907	34.05	2969	36.27	[illegible]	[illegible]	3088	40.78	3145	43.07	3213	45.68	3282	48.39	3350	51.14
12400	4366	2972	36.40	3033	[illegible]	3093	41.01	3151	43.36	3208	45.73	3263	48.12	3318	50.54	3385	53.36
13000	4577	3041	38.90	3099	41.25	[illegible]	[illegible]	3215	46.07	3271	48.51	3326	50.98	3380	53.48	3433	55.99
13600	4788	3110	41.54	3168	43.98	3224	46.44	3280	48.92	3335	51.45	3390	53.99	3443	56.56		

Figure 11. Case 3 ColPro System Retrofit

These cases show that the TIC filters can be retrofitted into existing M98 filter systems with only relatively minor changes.

Flow Balancing

As discussed previously in the Concept section, to facilitate an additional sorbent layer in the TIC filter, some dimensional changes were needed from the M98 filter to add additional volume. The first dimension considered was the internal diameter of the filter that defines the area available for airflow entering the filters. The minimum diameter is limited because excess restriction of this airflow will cause

a flow imbalance between the first and last filters in the housing. If too much flow passes through any one filter there will not be sufficient residence time of the air in the filter and thus the air will not be effectively filtered. A computational fluid dynamics (CFD) analysis was performed to determine what the minimum acceptable diameter should be. The analysis was performed for both U.S. Navy style housings and New World's OpenAire™ housings. The results of the analysis for the U.S. Navy style housings for both 3-deep and 5-deep filter housings are shown in Figure 12 and Figure 13. This analysis shows the comparison between the baseline M98 filter and a CBR/TIC filter with an inner diameter of about 8 inches. As can be seen in the velocity profile picture there is a significant increase in velocity through the center of the filter as expected with the decrease in area (Figure 12). However, the flow through each filter has very little change from the baseline M98 filter size. In fact, the flow balance is slightly better with the TIC filters. This can be seen in the radial velocity graphs (Figure 13). In the graph, each plateau represents a filter with the ideal graph being flat showing all filters with equal velocity and therefore equal flow. Although there is some difference between the individual filters, the difference is relatively minor. There are two (2) reasons for the slightly better flow balance with the CBR/TIC filters. First, the most significant axial flow restriction is on the outside of the filters and this does not change with the CBR/TIC filter. Second, the added pressure drop of the CBR/TIC filter helps to balance the flow through the filters. The analysis showed that the CBR/TIC HEPA filter could have an inner diameter of approximately 8 inches without causing any flow balance problems.

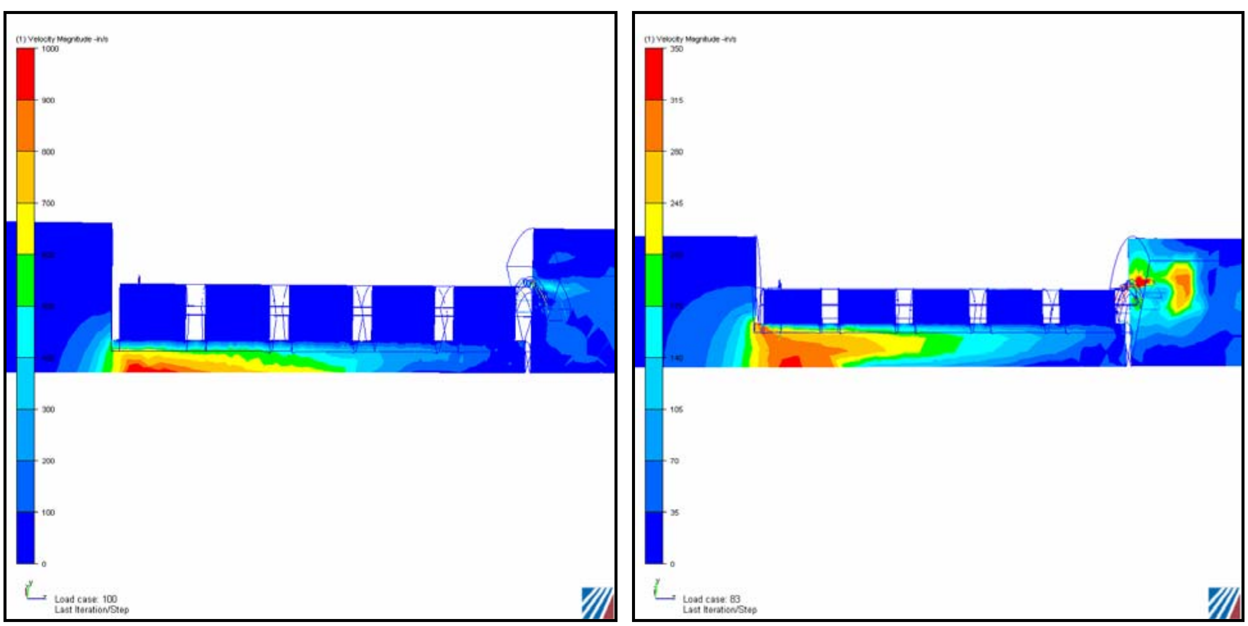


Figure 12. Navy Housing CFD Velocity Profile Comparison (TIC vs. M98Filters)

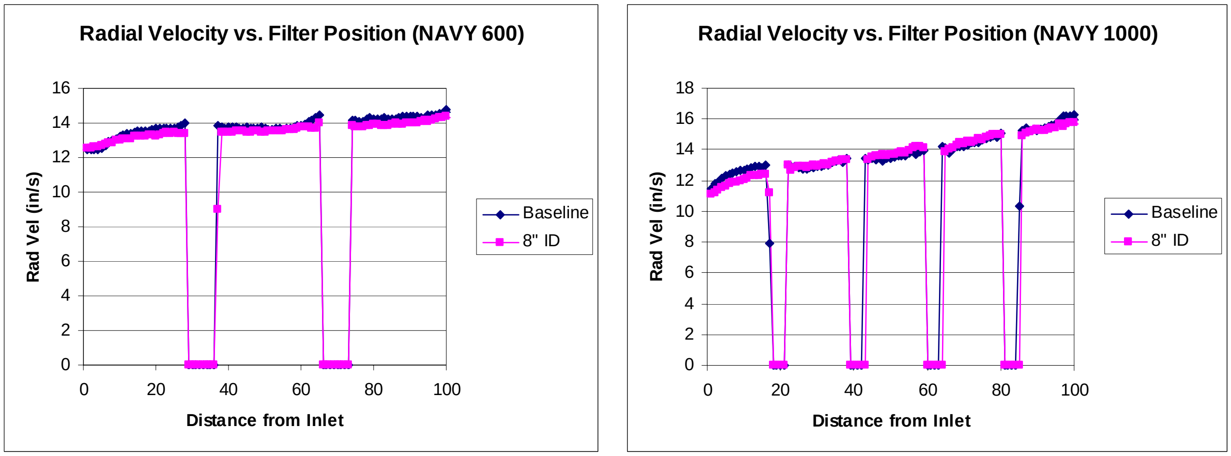


Figure 13. Navy Housings CFD Radial Velocity Graph (TIC vs. M98 Filters)

The results of the analysis for the 6-deep OpenAire style housings are shown in Figure 14 and Figure 15. This analysis also shows the comparison between the baseline M98 filter and a TIC filter with an inner diameter of about 8 inches. As can be seen in the velocity profile picture there is a significant increase in velocity through the center of the filter as expected with the decrease in area (Figure 14). Again, the flow through each filter has very little change from the baseline M98 filter size. In this case, the CBR/TIC filter flow balance is slightly worse than with the M98 filters, but the balance is still better than that shown for the U.S. Navy-style housings. This can be seen in the radial velocity graph shown in Figure 15. In the OpenAire housing the flow restriction is removed from the outside of the filters so the center flow restriction while still minor is larger than the outside restriction. The added pressure drop of the CBR/TIC filter still helps to balance the flow through the filters. The analysis of the OpenAire housing also shows that an inner space diameter of approximately 8 inches was acceptable.

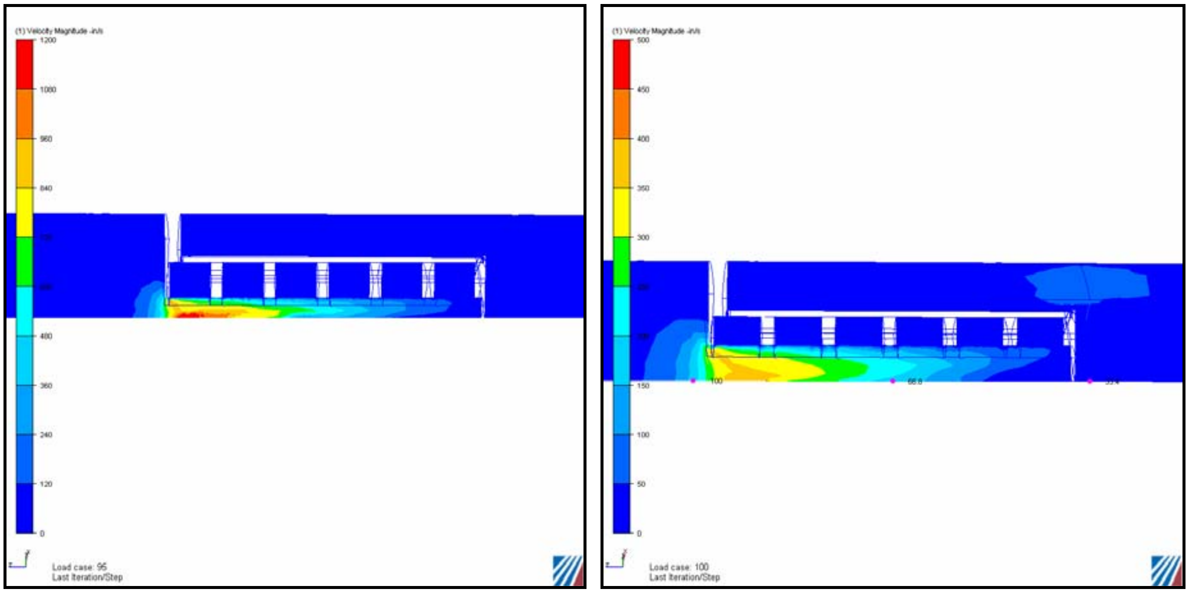


Figure 14. OpenAire Housing CFD Velocity Profile Comparison (TIC vs. M98 Filters)

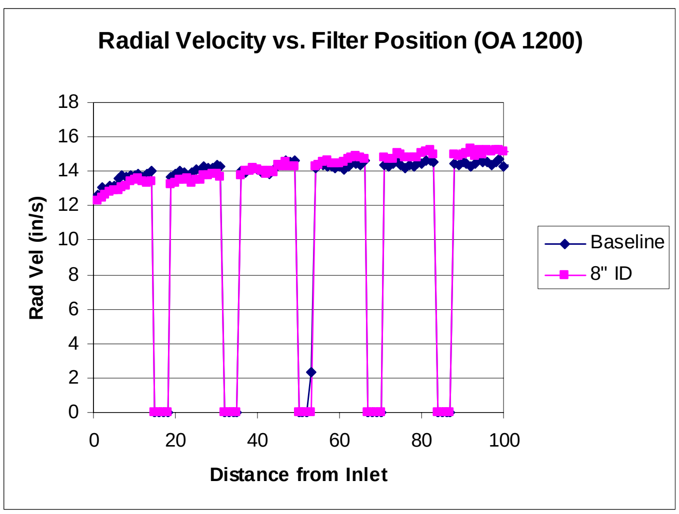


Figure 15. OpenAire Housing CFD Radial Velocity Graph (TIC vs. M98 Filter)

HEPA FILTER DEVELOPMENT

Design

As discussed in the Concept section of this report two (2) different HEPA designs were completed for this project. The single HEPA filter used with both the ECBC filter and the Hunter filter is discussed in further detail below. (The Portsmouth Aviation design is proprietary and will not be discussed in detail in this report. The Portsmouth Aviation design is packaged together with the gas filter similar to the NATO style filters.)

In order to increase the capabilities of the CBR/TIC gas filter above the M98 gas filter additional adsorbent media is required. This is a result of maintaining nearly the same protection against CWA and adding TIC gas capabilities. This subsequently requires the inside diameter of the TIC gas filter to become smaller since the new CBR/TIC filter must fit into the existing M98 filter housings and thus the outside diameter is fixed. Because the CBR/TIC gas filter is increasing in size (decreasing inside diameter) the new particulate filter diameter must decrease while the filter must still maintain HEPA quality filtration. This size reduction proved to be the largest obstacle in the design of the particulate portion of the filter set.

In order to reduce any flow balancing issues the inside diameter (ID) was set at a minimum of 7.8 inches. Inside diameters smaller than 7.8 inches would cause the flow to become imbalanced in longer filter housings. Additionally, as the ID of the filter decreased, fewer filter pleats could fit into the inner circumference, thus, the required filtration media also limited the minimum ID. The length of the filter was constrained by the length of the M98 filter, since these CBR/TIC particulate filters are designed to be direct replacements in the current M98 filter housings. Therefore, the only variable with a large latitude of freedom was the outside diameter of the filter.

Keeping the outside diameter of the particulate filter small would permit more absorbent media to be incorporated into the gas filter portion of the filter set. However, making the particulate filter outside diameter too small would result in loss of HEPA quality filtration, loss of filter loading capabilities, and an increase in pressure drop through the filter. A compromise between estimated filter performance and the amount of adsorbent material set the outside diameter of the particulate filter at 13.47 inches. Other key particulate filter dimensions are shown in Table 3. By using a custom pleated Lydall 4531 filter media it was estimated by Keystone Filter Division (the pleat pack manufacturer) that the filters would

maintain HEPA quality filtration, have a pressure drop of 0.31 iwg, and a have decreased dust loading capacity. The dust loading capacity was the biggest unknown during this stage of the design.

Filter Outside Diameter (Maximum)	13.47	in
Filter Inside Diameter (Minimum)	7.80	in
Filter Length (Maximum)	10.19	in
Filter Media Outside Diameter	13.00	in
Filter Media Inside Diameter	8.26	in
Pleat Density	9.0	pleats/in

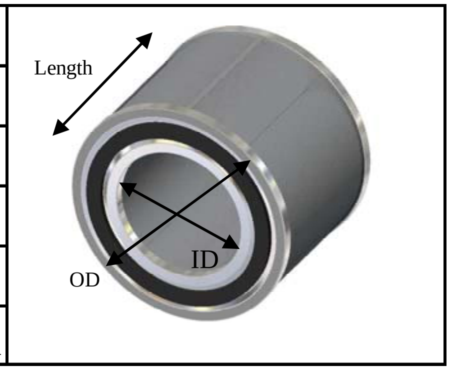


Table 3. CBR/TIC HEPA Filter Critical Dimensions

<u>Assembly</u>

The particulate filter is constructed as shown in the exploded view in Figure 16. The filter consists of pleated Lydall 4531 filter media enclosed in an inner and outer liner. The liners are constructed of galvanized flattened expanded steel sheets which are seam welded to produce the cylindrical shape of the filter. The inner liner, outer liner, and the pleated media are held in place on each end by the two aluminum covers. The covers are attached to these parts with a heat cured potting adhesive. Neoprene rubber face gaskets are adhered to each end of the particulate filter for airtight sealing.

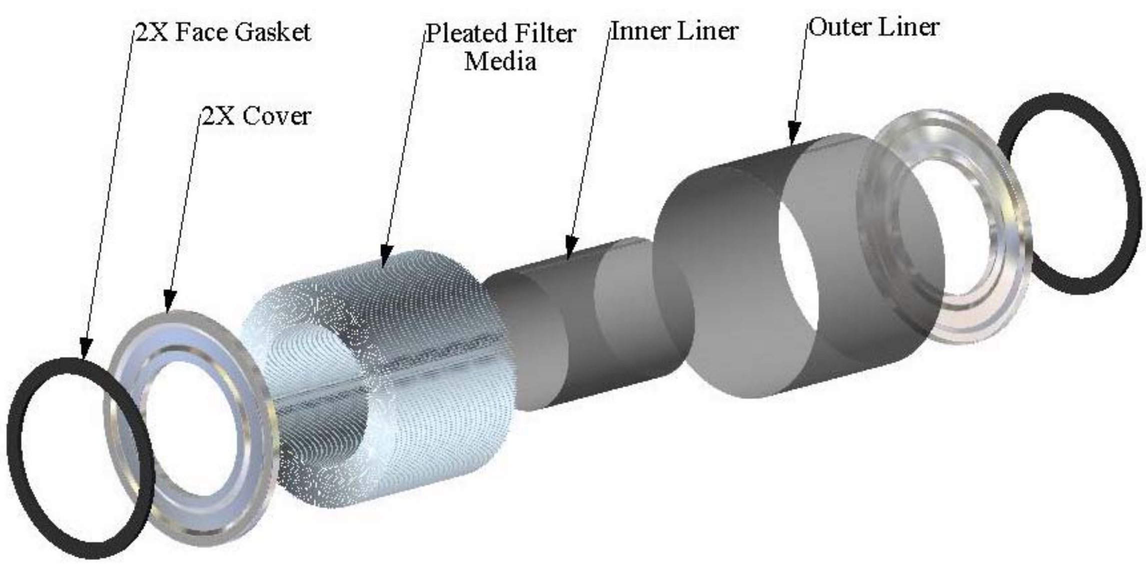


Figure 16. CBR/TIC HEPA Filter Assembly Exploded View

Hunter, the manufacture of the M98 filter set, assisted in assembling the particulate filters at their Mansfield, OH facility. The filters were assembled using the same methods and tools as the M98 particulate filter. A completed particulate filter is shown in Figure 17. The only problem that arose while assembling the filters was a fairly random separation of the pleats on the outside diameter of the pleat pack. This problem was not expected to cause a significant performance reduction for the particulate filter.

Figure 17. CBR/TIC HEPA Filter

A total of 25 filters were produced to fit in both the ECBC and Hunter gas filter designs. Both of these CBR/TIC gas filter designs have the same volume of adsorbent and as a result they can both utilize the same particulate filter. The CBR/TIC filter designed and built by PA will incorporate a particulate and gas filter into one (1) assembly. Consequently, the Portsmouth Aviation particulate filter differs from the particulate filter described above.

GAS FILTER DEVELOPMENT

Design

After design of the CBR/TIC HEPA filter was complete, the space for the CBR/TIC gas filter was defined. The remaining selections for the design of the gas filter beds were the selection of a sorbent for TIC removal and division of the beds to determine the relative thicknesses of the TIC and CWA layers. In addition, the design of the mechanical portions of the filter and the assembly methods for the filter were determined.

As discussed above, there are three (3) separate CBR/TIC filter designs by three groups. Both the ECBC and Hunter designs are discussed in this section.

The Portsmouth Aviation design uses the same Guild zeolite media as the ECBC-designed sorbent beds as the ECBC-designed gas filter. The Portsmouth Aviation filters are proprietary and were not funded under the DARPA contract as were the ECBC/New World and Hunter filters and so will not be discussed in detail.

Sorbent Selection

The ECBC group had worked with and tested a media developed by Guild Associates, Inc. to filter a variety of chemicals previous to the start of this particular project. After discussions with ECBC on the threat scenario for this project, they selected the Guild media BF-38-3S part number SFM-1527 based on its ability to effectively remove both ammonia and ethylene oxide. This media is a zeolite-based and has a sulfuric acid treatment.

Hunter worked with the J.M. Huber Corporation to develop a sorbent media that would remove the TICs of concern for this project. They selected part number 989-18B as the material for use in their design of the CBR/TIC filters.

Bed Design

After selection of a CBR/TIC filtration media designs of the bed division were completed by all groups and initial tube tests were performed to verify the initial designs. An example of the details from the calculations in designing the filter bed is shown below in Figure 18 for the ECBC-designed bed.

TIC Filter Concept I			
	ASZM-T Bed	TIC Adsorbent Bed	Overall Adsorbent Bed
Adsorbent Bed Height, inches	9.634	9.634	9.634
Adsorbent Bed Height, cm	24.47	24.47	24.47
Inside Diameter, inches	13.75	18.24	13.75
Inside Diameter, cm	34.93	46.33	34.93
Inside Surface Area, cm2	2,685	3,561	2,685
Bed Depth, cm	5.7	3.52	9.22
Bed Depth, inches	2.24	1.39	3.63
Outside Diameter, inches	18.24	21.01	21.01
Outside Diameter, cm	46.33	53.37	53.37
Outside Surface Area, cm2	3,561	4,102	4,102
Flow Rate, cfm	200	200	200
Flow Rate, cm3/s	94,390	94,390	94,390
Inside AFV, cm/s	35.2	26.5	35.2
Outside AFV, cm/s	26.5	23.0	23.0
Log Mean AFV, cm/s	30.6	24.7	28.7
Bed Depth, cm	5.7	3.52	9.22
Residence Time, s	0.186	0.142	0.322
Adsorbent Volume, cm3	17,802	13,488	31,290
Residence time, s	0.189	0.143	0.331

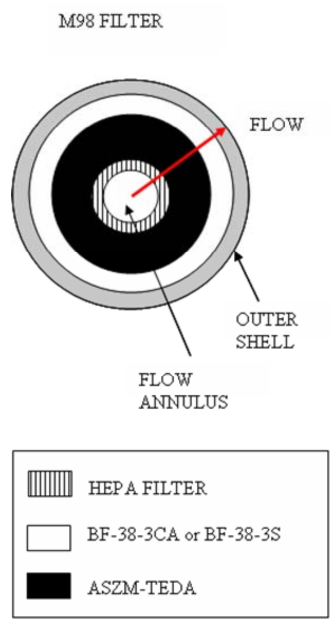


Figure 18. ECBC Filter Bed Sample Calculation Detail

Assembly

The gas filter is constructed as shown in the exploded view in Figure 19. The filter consists of three (3) liners, an inner and outer liner and a spacer that separates the two (2) filter beds. The inner and outer liners are constructed of perforated aluminum sheets which are seam welded to produce the cylindrical shape of the filter, identical to the M98 liners. The spacer is made of stainless steel perforated sheet metal. The inner liner, outer liner, and the spacer are held in place on each end by the two (2) aluminum covers. The inner and outer liners are riveted to the end caps. The spacer is attached with adhesive to the bottom end cover and is spaced by the compression pads on the top end. EPDM foam compression pads are placed on top of the adsorbent beds before sealing the filter to compress and hold the bed in place. After the filter is filled the covers are pressed down on the compression pad and riveted in place. Neoprene rubber face gaskets are adhered to each end of the particulate filter for an airtight seal.

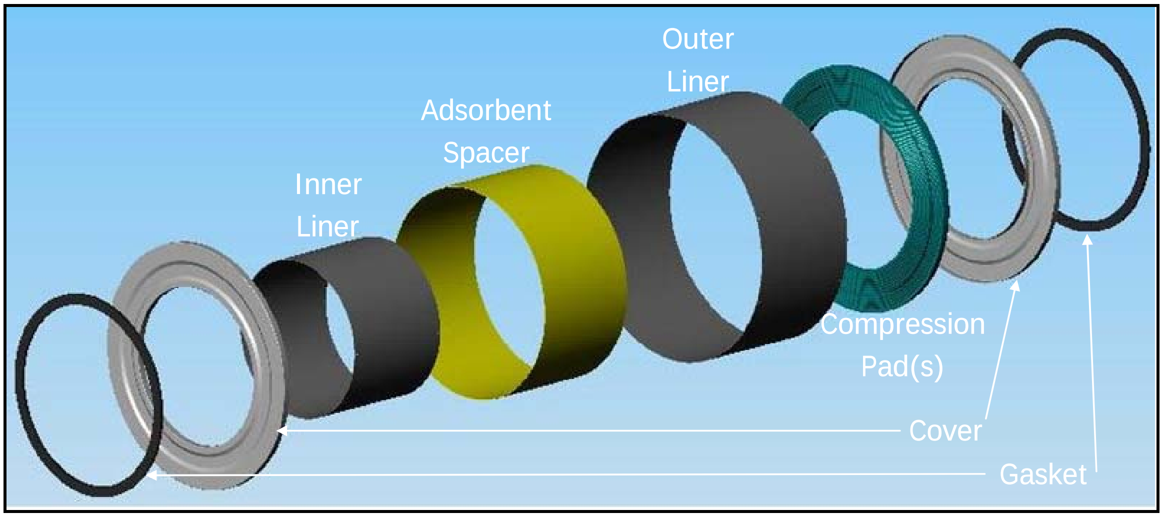


Figure 19. CBR/TIC Gas Filter Assembly Exploded View

Hunter, together with New World personnel assembled the ECBC/New World filters at their Mansfield, OH facility. Hunter assembled the filter they designed and Portsmouth Aviation assembled their filter design. The filters were assembled using the same methods and tools as the M98 particulate filter. A completed ECBC/New World filter set is shown in Figure 20 and a Portsmouth Aviation filter is shown in Figure 21. Some problems were encountered during the filling of the ECBC/New World filter. Hunter uses a proprietary fill tower to fill the M98 filters with carbon. Hunter modified a fill tower to fill the CBR/TIC filters. Unfortunately, the fill tower did not mate well with the spacer separating the two (2) adsorbent beds. The original plan was to fill the two (2) beds simultaneously; however, the mating caused problems with that approach including mixing of the medias and uneven filling. The first five (5) filters were filled with the simultaneous method. A second method was tried where the interior carbon bed was first filled and then masked, then the exterior zeolite bed filled which resulted in a better overall fill. Therefore, the remaining 10 filters were filled in this manner. In the end, 15 complete filters were assembled of the ECBC/New World design, of which 10 were originally delivered to ECBC for testing. Hunter also built 15 filters of which 10 filters were delivered to ECBC for testing, and Portsmouth Aviation delivered three (3) filters.

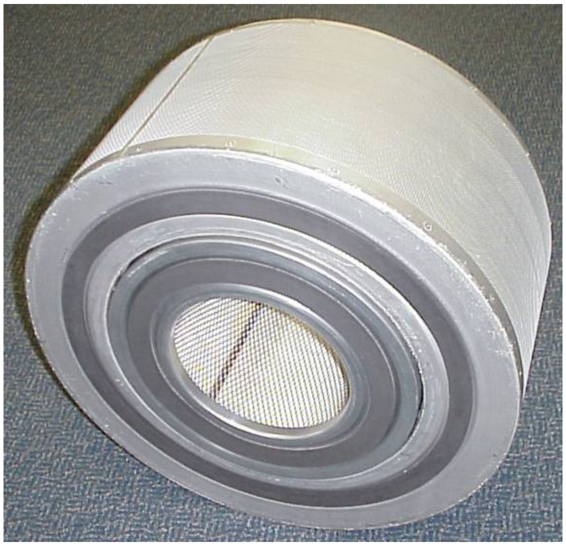


Figure 20. ECBC/New World CBR/TIC Filter Set

Figure 21. Portsmouth Aviation CBR/TIC Filter Set

FILTER TESTING

Particulate Filters

The majority of the testing of the particulate filters was conducted at New World's lab. Some preliminary tests were also conducted at Hunter Manufacturing's facility in Mansfield, OH. The tests completed at the Mansfield facility are the same tests used to verify the performance of regular production M98 particulate filter. The testing included efficiency and pressure drop tests on all 25 of the filters at their rated flow rate of 200 cfm. Dust capacity testing was also completed on a random sample of six (6) of the 25 filters at the rated flow rate.

Figure 22 shows New World's test stand used in this investigation. This test stand was previously developed for dust capacity testing as described in New World's "200 cfm HEPA Filter Media Evaluation" report. With this test stand it is also possible to test filter efficiencies using Poly-Alpha Olefin (PAO).

Figure 22. Filter Efficiency and Dust Capacity Test Stand

Particulate Filters

Efficiency tests were completed at both Hunter and New World's facilities. The filters were tested at their rated flow rate of 200 cfm. At both facilities the filters were challenged with PAO using a Laskin nozzle aerosol generator. The PAO polydispersed oil mist aerosol produce by the generator has a mean particle diameter of approximately 0.3 microns. Both upstream and downstream aerosol concentrations were measured with a calibrated photometer. These two (2) concentrations were then used to calculate the filter efficiencies at a mean particle diameter of 0.3 microns. All 25 filters had

efficiencies of over 99.995% at the indicated particle size. This is well above the 99.97% minimal efficiency requirement for a HEPA filter designation.

Particulate Filters

The dust loading tests performed for this project used a Schenck Accurate gravimetric feeder to supply Arizona Road Dust (ISO 12103-1, A2) to the test stand upstream of the filter. The basic test procedure used for all of the filter dust capacity tests is as follows:

1. Weigh the filter to determine "clean" mass
2. Install the filter into the test stand
3. Perform efficiency test on the clean filter with 200 cfm flow
4. Perform dust capacity test with a constant 200 cfm flow and nominal 0.75 lb/hr dust feed rate
5. Perform efficiency test on the dirty filter with 200 cfm flow
6. Remove filter from stand and weigh to determine the amount of dust loaded

The entire dust-loading procedure was run in one (1) day, with the fans running continuously. The test stand was configured to deliver a known amount of dust at a constant rate to the test filter while measuring the pressure drop across the filter. The pressure verses dust delivered data for the six (6) filters tested is shown in Figure 23. Figure 24 shows a typical CBR/TIC particulate filter following the completion of a dust loading test. It is evident from this figure that the dust loaded uniformly on the filter media throughout the test. This is typical for all the dust loading tests completed.

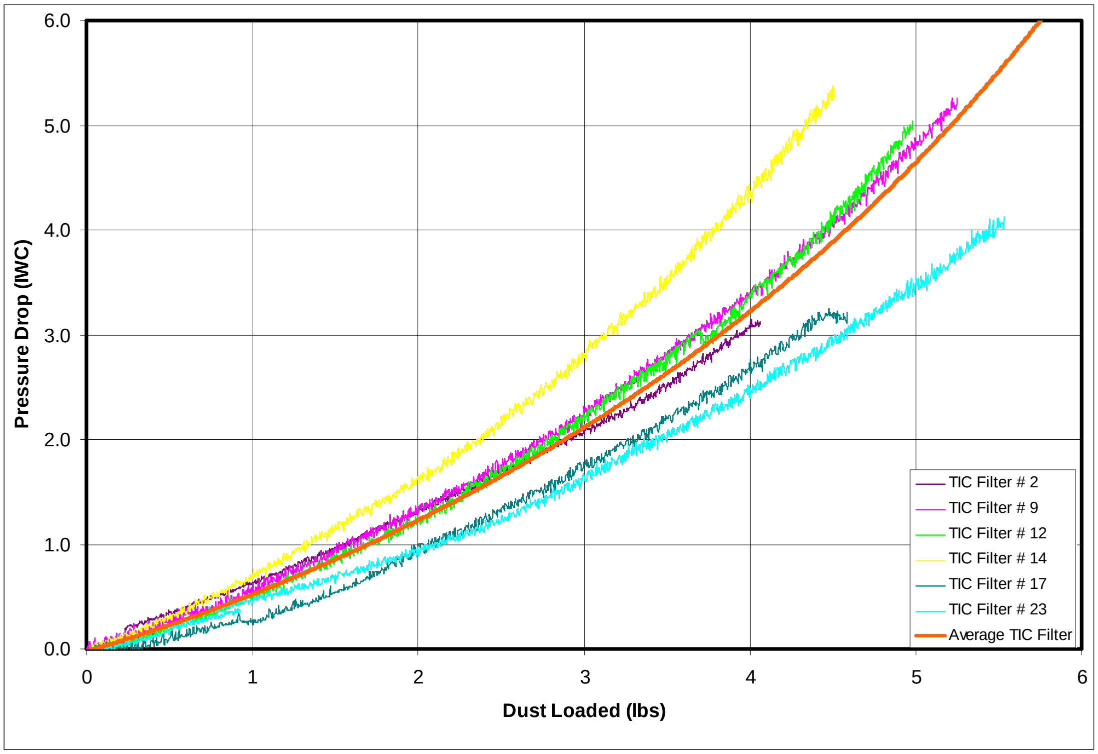


Figure 23. CBR/TIC Particulate Filter Dust Loading Tests

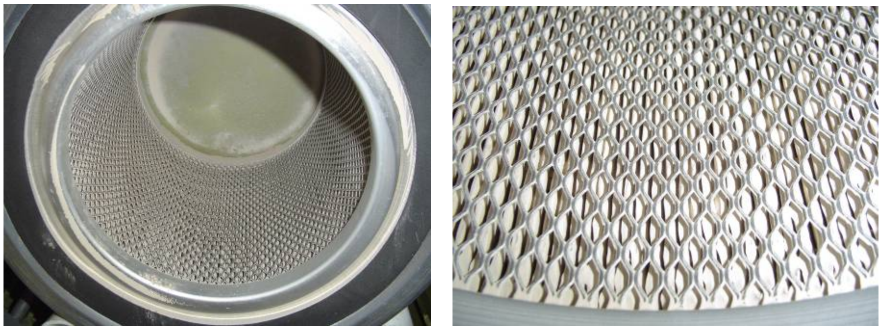


Figure 24. Dust Loaded CBR/TIC Filter

The life of filters is generally determined by the point at which the pressure drop across the filter reaches a predetermined value. Therefore, it is valuable to compare the dust loading results of the CBR/TIC particulate filter to those of the current M98 particulate filter. Figure 25 compares the dust loading results of averaged data from tests of both filter types. As shown in the figure, the CBR/TIC particulate filter holds 70% and 74% of the dust as the M98 particulate filter at an increase in pressure drop of 2 and 3 i.w.c., respectively. As a result it is safe to conclude that the CBR/TIC particulate filter will have a filter life of approximately 70% of the M98 particulate filter if used in the same filtration environment.

According to MIL-PRF-51526A(EA) the TIC particulate filter meets the performance specification for the 200 cfm particulate filter requirement for dust loading capabilities under section 3.5.4. This specification required that the 200 cfm filter must deliver the rated airflow at a resistance of no greater than 5.7 i.w.c. when uniformly loaded with 4.4 lbs of dust per Class A2 of ISO 12103-1.

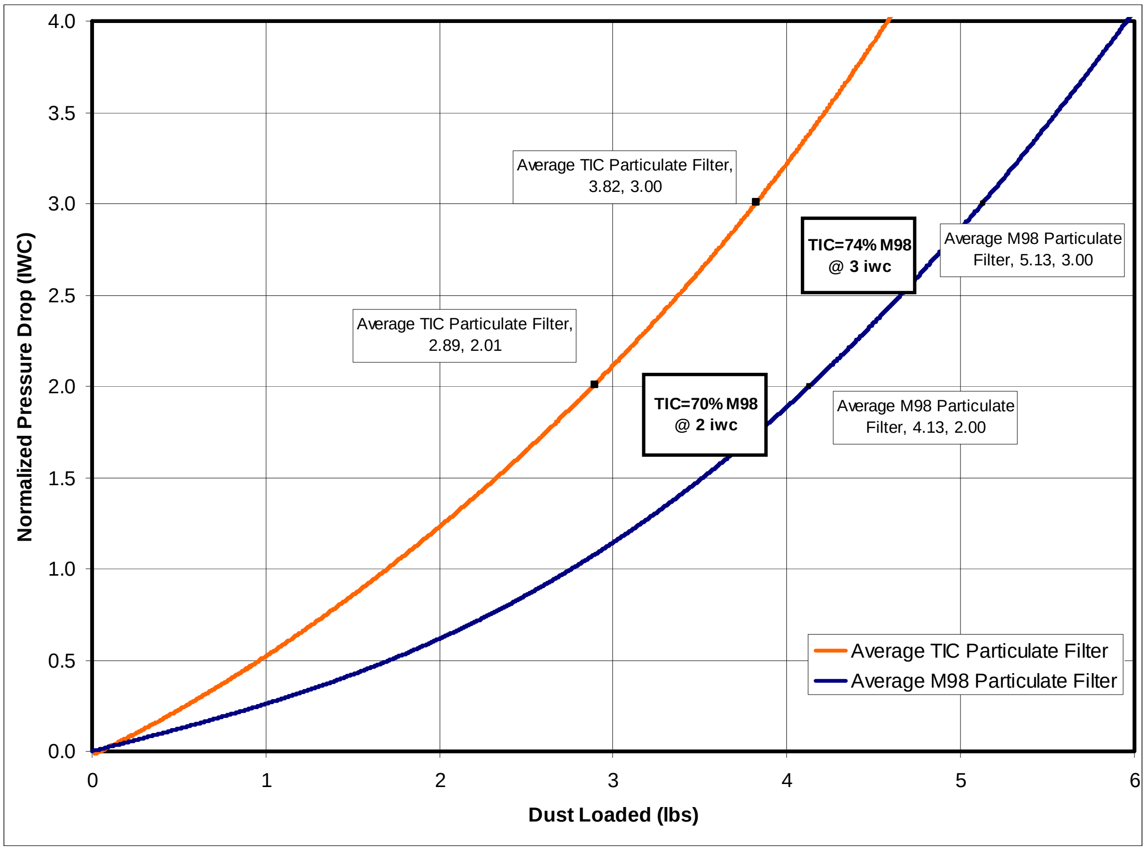


Figure 25. CBR/TIC Particulate Filter vs. M98 Particulate Filter Dust Loading Tests

<u>Pressure Drop</u>

The pressure drop through the clean CBR/TIC particulate filters was measured at both Hunter and New World. The filters were tested at their rated flow rate of 200 cfm. The average pressure drop though the CBR/TIC particulate filters was 0.46 i.w.c. This value is very similar to the pressure drop through a clean M98 particulate filter (~ 0.5 i.w.c). This similarity is a result of the filters having very similar face velocities/media velocities through the filter media.

<u>Gas Filters</u>

The testing of the CBR/TIC gas filters was conducted at the ECBC Filter Test Facility (FTF). ECBC is the U.S. Army's center for expertise in chemical filtration and have the only known facility

capable of performing full scale filter tests for the chemicals of concern. The following test plan was developed for testing the CBR/TIC filters:

ECBC shall test 10 200 cfm ECBC radial flow CBR/TIC filters to determine the filter life. The following chemical tests will be performed:

- DMMP - 2 tests
- CK - 2 tests
- Ammonia - 3 tests
- Ethylene Oxide - 3 tests

ECBC shall test 10 200 cfm Hunter fadial flow CBR/TIC filters to determine the filter life. The following chemical tests will be performed:

- DMMP - 2 tests
- CK - 2 tests
- Ammonia - 3 tests
- Ethylene Oxide - 3 tests

ECBC shall test three (3) 200 cfm Portsmouth Aviation radial flow CBR/TIC filters to determine the filter life. The following chemical tests will be performed:

- DMMP - 1 test
- Ammonia - 1 test
- Ethylene Oxide - 1 test

The chemical tests are performed by subjecting the filters to a known concentration of the challenge chemical and recording the time until the chemical breaks through the filter. The chemical concentration (usually in mg/m^3) multiplied by the time to breakthough (usually in minutes) gives the capacity of the filter in Ct (usually in $mg\text{-}min/m^3$). DMMP and CK are the chemicals generally used to represent the chemical warfare gases for which the base M98 filter was designed. Ammonia and ethylene oxide are the TICs chosen as the design basis for this filter as discussed in the TIC Scenario section of this report.

The results from the DMMP filter life tests are shown below in Figure 26. As seen in the graph all filters exceeded both the TIC target life as well as the M98 requirement. This capacity was expected

as the TIC adsorbent layer added some additional DMMP capacity to the filter beyond the standard ASZM-TEDA carbon layer. Unfortunately, the Portsmouth Aviation filter was not able to be tested for DMMP capacity as due to problems with delivery through customs the filters were delivered after the DMMP testing had been completed.

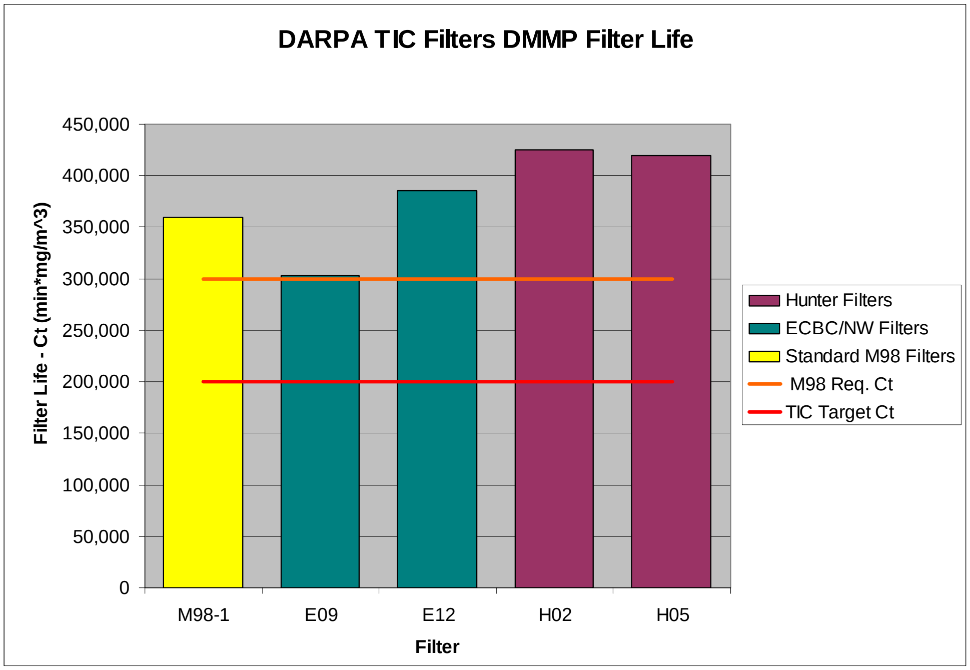


Figure 26. CBR/TIC Filters DMMP Filter Life

The results from the CK filter life tests are shown below in Figure 27. As seen in the graph all filters fell below the predicted filter life. The Hunter filters while lower than expected were still in an acceptable range. However, the ECBC filters lasted only a few minutes and were considered to have failed the CK test. Originally, only two (2) filters of each type were slated for CK testing. After the ECBC filters failed the CK test, discussions were held with ECBC personnel to attempt to determine the cause for this failure. Through those discussions it was decided to test two (2) additional ECBC filters to eliminate an aberrant filter or two as the cause for the failures.

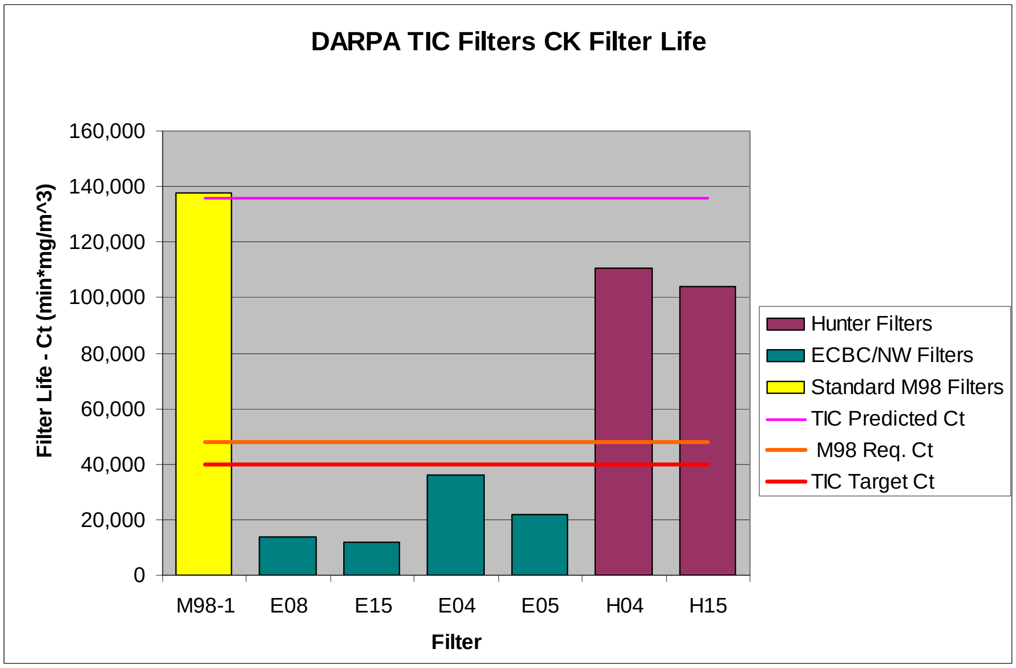


Figure 27. CBR/TIC Filters CK Filter Life

There were two (2) possible causes for the failure. First, during environmental equilibration to 80% relative humidity an unknown contaminant was measured coming off the filter. The contaminant was seen for all ECBC filters. This contaminant could have limited the CK filter life. Second, the failure source could have been caused by the problems in filling the filters discussed above. As seen in Figure 28 and discussed previously, there was some mixing of adsorbents during the filling process, particularly for the first filters made. A high concentration of zeolite in the carbon bed could provide a path for the CK gas to pass through the bed much more quickly and thus “fail” the test. However, as four (4) different filters were tested including filters from both fill techniques and all showed the same failure; it is likely that the contaminant and not the mixing caused the failure.

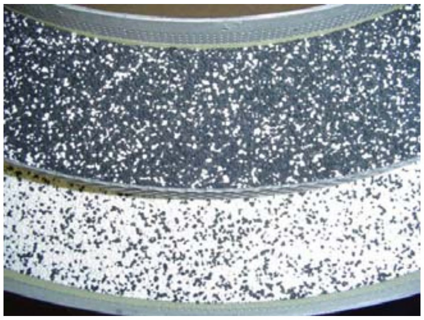


Figure 28. ECBC CBR/TIC Filter Adsorbent Bed Mixing During Filling

Filter life for CK and the CWAs it represents are very susceptible to reductions in filter life due to aging. For that reason, the CK life requirement was chosen as the filter life after two years. Aging testing of two years is outside the scope of this project. However, based on measured M98 filter life data provided by ECBC, a decay rate can be predicted for the ASZM-TEDA carbon used in these filters. The predictions based on that decay rate are shown below in Figure 29. The pink line shows the predicted filter life starting with the average unaged CK life measured for the Hunter filters. As shown, the life is expected to reduce below the CBR/TIC filter requirement before two years. If these filters were used as is, the filters would probably require replacement sooner than the M98 filter depending upon the expected attack scenario. The green line shows the desired minimum predicted aging filter life for the CBR/TIC filters. This decay rate would require an unaged filter life of approximately 128,000 mg-min/m3. This is below the expected filter life of 136,000 for these CBR/TIC filters. If the problems can be corrected and CK life achieved close to the expected life, this filter should pass the CK aged filter life requirement.

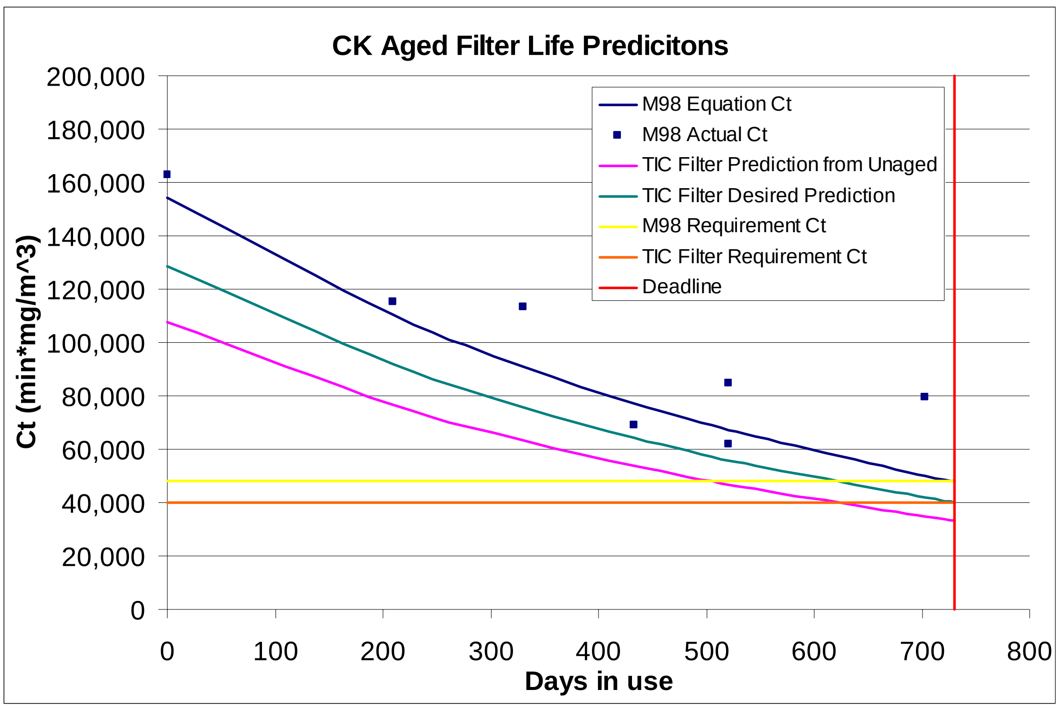


Figure 29. CBR/TIC Filters Aged CK Filter Life Predicitions

The results from the ammonia filter life tests are shown below in Figure 30. As seen in the graph all filters exceeded the TIC target life and are significantly better than the M98 filter at removing ammonia.

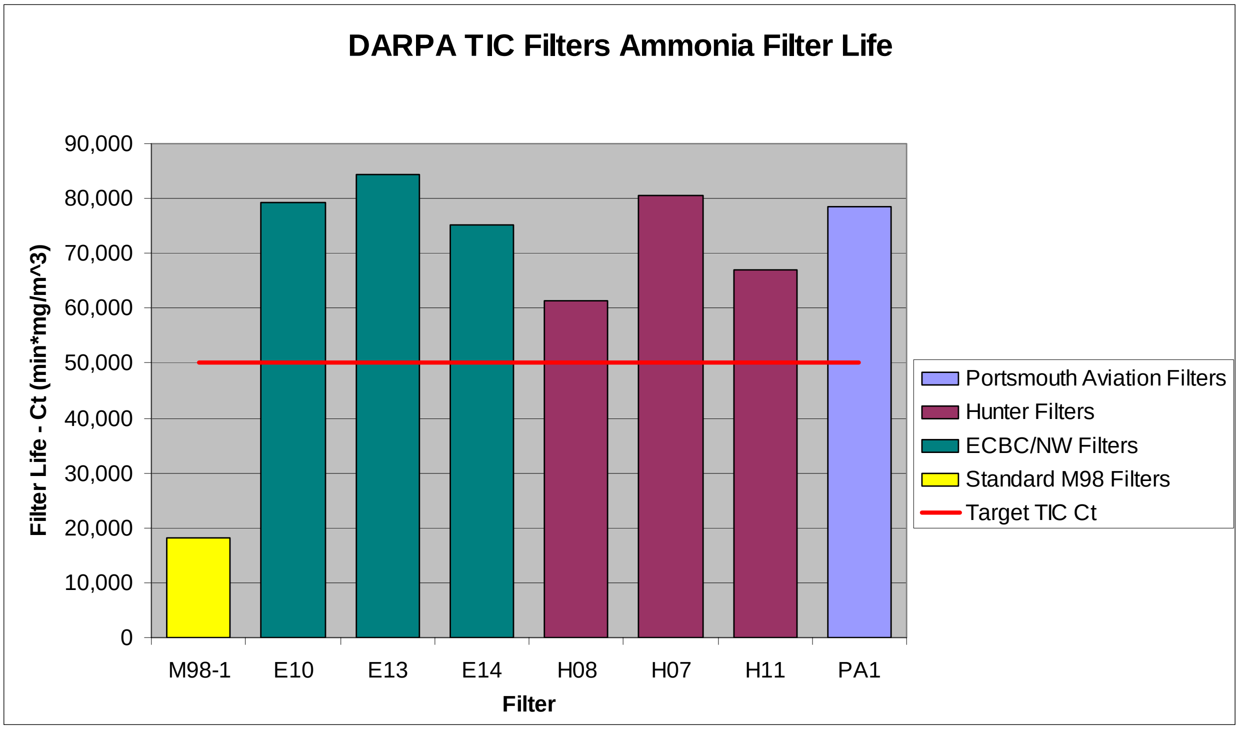


Figure 30. CBR/TIC Filters Ammonia Filter Life

The measured performance of the filters when exposed to ethylene oxide is shown in Figure 31. The ECBC filters have a wide range of capacities. This could be caused by the same contaminant discussed above in the CK life discussion. A possibly related observation was that zeolite particles in the packaging of the ECBC filters had changed to a pink or purple color. An untested filter was disassembled to look for possible causes for the problems and a pink layer of granules around the outside of the filter as shown in Figure 32. This particular ECBC filter was assembled at the Hunter facility and subsequently sealed in an airtight container until the picture in Figure 32 was taken. Though it is currently unknown, New World expects that the pink layer was present in all the tested ECBC filters. It is important to note that the Portsmouth Aviation filter passed the ethylene oxide test utilizing the same Guild zeolite material as the ECBC filter. The Hunter filters exceeded the filter life requirement.

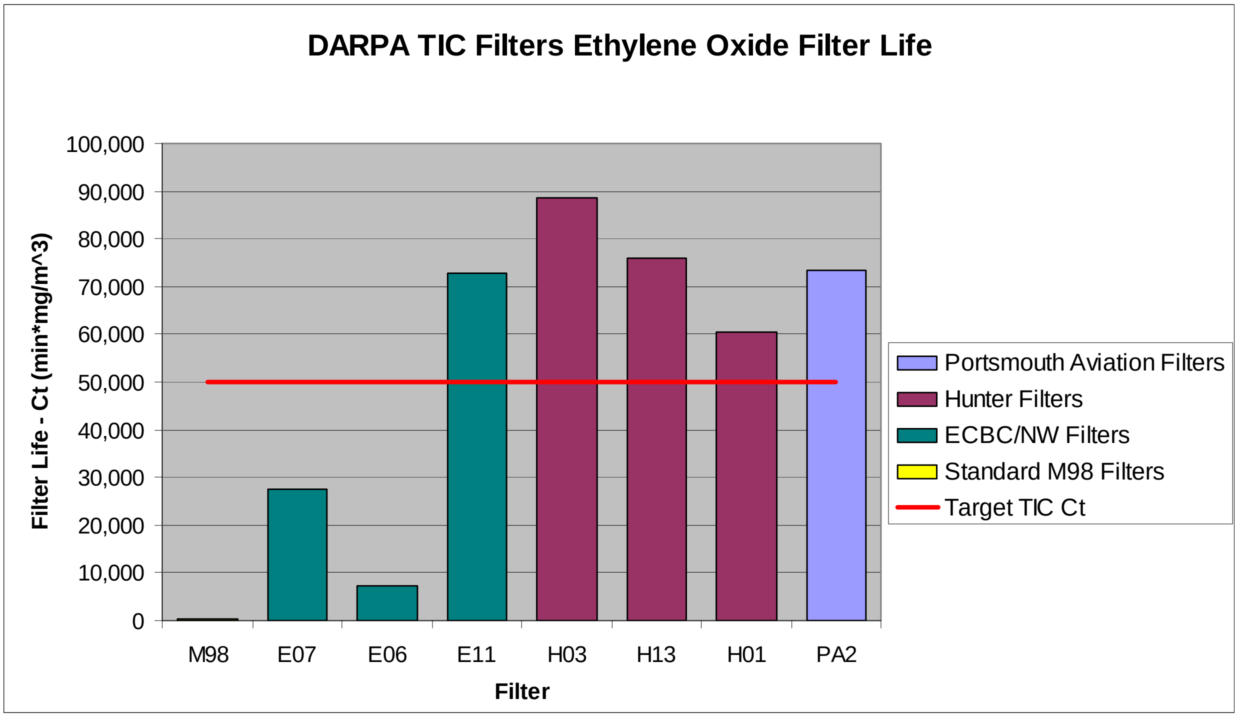


Figure 31. CBR/TIC Filters Ethylene Oxide Filter Life

Figure 32. Pink Zeolite from Filter Disassembly

A summary of the filter lives for each filter design is shown below in Figure 33. The Hunter filters passed all tests with the somewhat low CK life as discussed previously. The Portsmouth Aviation filters also passed all tests, but were not tested against DMMP and CK due to the low number of filters delivered and the late delivery. The ECBC filters failed CK and ethylene oxide tests as discussed, and New World suspects that the failure was due to contaminated Guild and/or ASZM-TEDA sorbents.

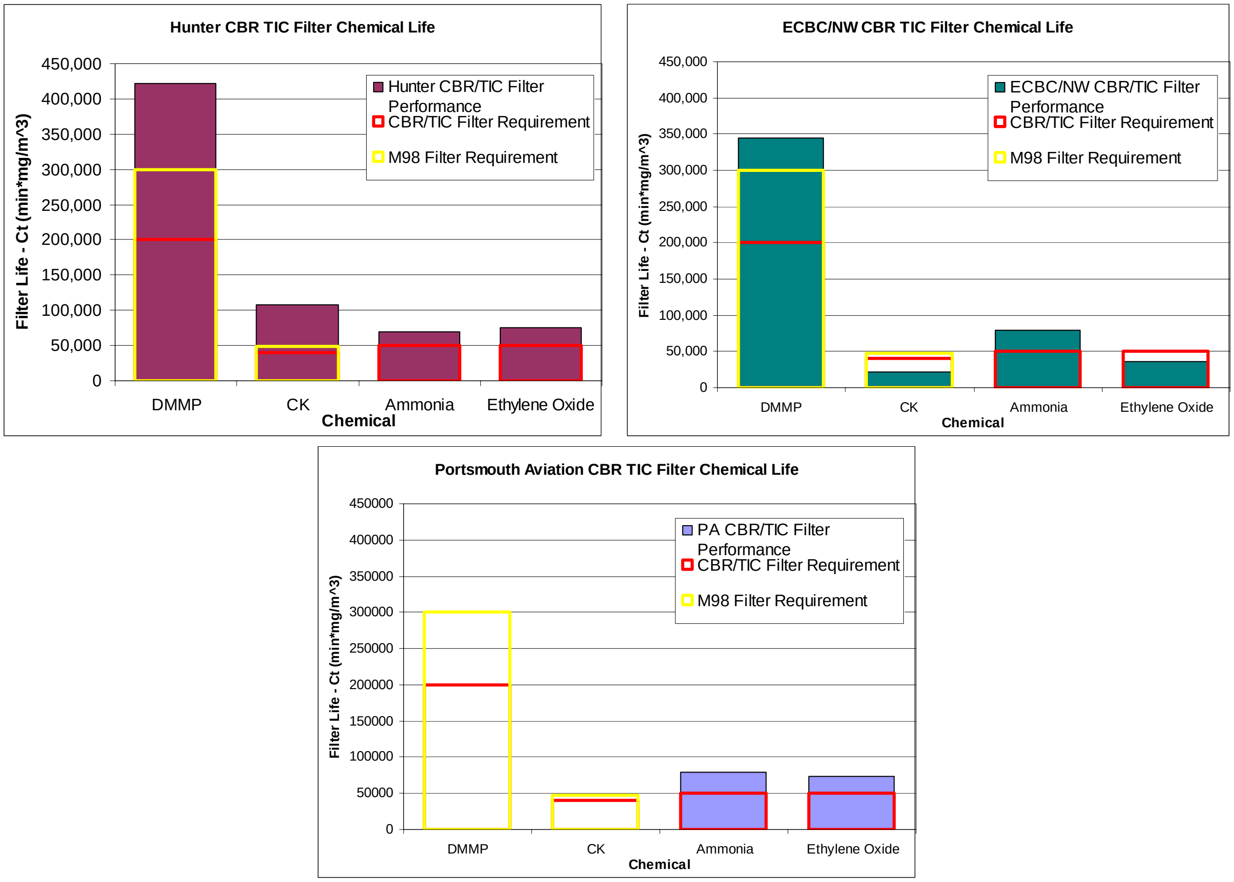


Figure 33. CBR/TIC Filter Summary by Design

CONCLUSIONS/NEXT STEPS

New World in association with ECBC, Hunter, and Portsmouth Aviation has proved the concept of a layered bed CBR/TIC filter. Filters have been developed that provide TIC protection in addition to the CBR protection provided by the standard M98 filter set. This concept can also be extended to other TICs in addition to the ones selected for this effort. A layered filter can be made with a sorbent selected for the specific TIC(s) of concern for a particular application. It has been shown that it is possible to retrofit these filters into existing ColPro systems with housings designed to hold the M98 filter. With only relatively minor modifications to accommodate the increase in pressure drop and a replacement housing cover, these filters can be installed in any land based ColPro system. These filters are complete such that with minor modifications they could be ready for production very quickly if there was a demand for them.

The Hunter gas filters with the ASZM-TEDA/J.M. Huber media layers performed well on the DMMP, ammonia, and ethylene oxide tests. Although the CK performance for the Hunter gas filters was slightly below predicted levels, they perform sufficiently well to provide protection. The Portsmouth Aviation gas filters with the ASZM-TEDA/Guild media layers performed well on the ammonia and ethylene oxide tests, but were not tested with DMMP and CK. Also, only two (2) Portsmouth Aviation filters were tested (one for each of the TIC gases), so assessments of filter-to-filter variation cannot be made. The ECBC/New World gas filters with the ASZM-TEDA/Guild media layers (the same media as for the Portsmouth Aviation filters, but in slightly different depths) performed well on the DMMP and ammonia tests, but performed poorly and had great variability when tested with CK and ethylene oxide. New World suspects either contamination of both beds or mixing of media in the bed layers is responsible for the poor performance.

In order to prepare for production and in-field use, the following steps are recommended:

- Identify the reason(s) for the poor performance of the ECBC/New World gas filters.
- Change the compression pad to an improved material like the M98 compression pad in order to insure a tighter packed carbon bed.
- Improve the fill tower to better seal with the filter liners during the filling process.
- Build and test the redesigned filter housing covers.
- Study the relative effects of changes in bed thickness on filter capacity and pressure drop through the filter. The large pressure drop through these filters may be prohibitive in some

applications and a compromise with filter capacity may be acceptable to reduce the pressure drop for some applications.

- Perform qualification tests for this filter to include:
  - Environmental
  - Shock
  - Vibration